A georeferenced river quality model

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Abstract Water quality models have reached a high degree of sophistication, but their weak side remains user interface and output georeferencing. The aim of this paper is to propose an interfacing procedure between two widespread but specialised programming environments: ArcVIEW as a Geographical Information System (GIS) and Matlab as a scientific programming tool for numerical analysis. The proposed solution is based on a Dynamic Data Exchange (DDE) between the two programs in order to operate a Matlab-based water quality model from within the GIS environment. It is shown how special GIS objects must be created and how they operate to achieve the goal of having quality data created by the model placed on a geographical map, together with other site features.

Keywords Environmental management; geographical information systems; river water quality; simulation; systems analysis

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Introduction

Water quality models are now becoming very advanced in describing the dynamics of the aquatic environment and can produce a considerable amount of data. The problem that often arises is the most efficient way of presenting those data in their geographical context. On the other hand, the geographical processing of environmental information is equally developed and many advanced Geographical Information Systems (GIS) are now available (Lang, 1998; Johnston, 1998). However, the interaction between these two worlds has been very limited so far. To try to bridge the gap, this paper proposes a technique to interface a river quality model, developed in Matlab (The MathWorks Inc., USA) with a widespread GIS such as ArcVIEW (ESRI Inc., USA). The application follows the typical client/server philosophy and establishes a communication path through which data can be exchanged. The result is that simulations performed in the Matlab environment can be presented as features of a GIS project, with all the advantages of geographical referencing and integration with other features typical of a GIS environment, such as Digital Picture Processing (Kak and Rosenfeld, 1982).

The paper will present the features of this integrated application with the aid of the case study of a small river reach in Tuscany. It will be shown that this solution can provide a flexible way to take advantage of the characteristics of both environments.

An integrated application

An integrated application is viewed by the user as a single environment offering an extended set of functions. Normally a river quality modelling problem is initially conceived in the geographical context and the spatial features are the first to be considered when dealing with a river system. Therefore, in this application, the GIS will be the front-end and should incorporate the additional feature of water quality modelling. This choice is also justified by the fact that most water quality models have a fairly weak user interface, though they may be very strong in computational capabilities. Further, they have little, if any, built-in features for spatial placement of data. To integrate these two environments a client/server

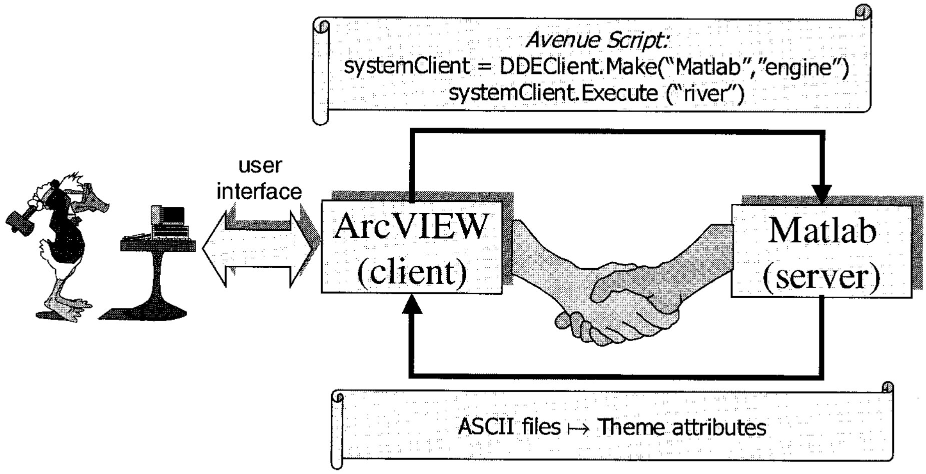

Figure 1 Simplified view of the client/server link between ArcVIEW and Matlab

architecture was envisaged, with ArcVIEW serving as a client and Matlab as the server. The data exchange between the two is performed through a very simple Inter Application Communication (IAC) such as a Dynamic Data Exchange (DDE) procedure, which is supported by both environments. The client serves also as a user interface, from which the river characteristics can be specified and the results of the simulation queried. Figure 1 gives a simplified view of how the client/server link can be established between these two resources.

ArcVIEW (ESRI, 1996a) has a procedural language, *Avenue* (ESRI, 1996b), to define "scripts" which can implement the DDE procedure: the first step is the opening of a dialog (DDEMake.client) in which the name of the application server (Matlab) and the topic (engine) is specified. Then, after the river model has been defined, the client issues an execute request to the Matlab server (systemClient.Execute ("river")), thus invoking the numerical procedure to solve the model equations and the output of the quality data. The numerical computation is totally under Matlab control and will be described in the next section, when dealing with the model features. The results are temporarily written into a set of ASCII files, which are then imported into the client for further graphical processing and presentation in the ArcVIEW context.

The interaction between the two computing environments is composed of two stages: pre-processing, post-processing, and user interface. They are now described in detail.

Pre-processing

In this phase the input data are entered through the ArcVIEW user interface. Two programming tools are needed for this: ArcINFO (ESRI, 1992a) which has the capability to define the geometry of the river over the geographical base, and ArcVIEW which uses this base to prepare the input data to the quality model. The two environments are conceived to work together in a complementary way, since ArcINFO has specific functions for data handling and processing, whereas ArcVIEW is more specialised in data representation and feature extraction from a geographical database. The most relevant features used in this pre-processing phase are:

- *Definition of the geometrical reference base*. The river system is represented as a cover, which is the basic geographical object in the ArcINFO environment. Its co-ordinates can be digitised from a traditional map or imported by a digital map, if it exists already. As a result, the river will be represented by a vector of significant co-ordinates. The ***cover***, however, contains more features than the simple river locations. In addition to spatial data, it can include descriptive information and topological relations among data, such as *connection*, *adjacency* and *inclusion*. A ***cover*** can also be viewed as a collection of homogeneous geometrical primitives (points, lines, surfaces) used to represent a geographical object. In this case, a river is represented as a series of lines, i.e. a *polyline*. The importance of the ***cover*** is that it establishes a link between spatial data and the descriptive features of the same object.

- *Dynamical segmentation*. To allow the data exchange between GIS and Matlab, the GIS geometric representation should be adapted to the data structure used by the mathematical model. In other words, the data generated by Matlab should be associated with corresponding ArcVIEW graphical primitives. Through *dynamic segmentation* (ESRI, 1992b) a logical structure can be superimposed on a physical topology. The ArcVIEW element corresponding to the river reach is the ***route***, representing a linear element to which attributes can be associated through a co-ordinate system starting from the ***route*** origin. Using this approach the river reach is partitioned into elements, hereafter called ***cells***, where the quality parameters are assumed to be homogeneous. A ***route*** is created in ArcINFO and imported into ArcVIEW where it becomes a ***theme***. Thus an item is created where the quality data can be stored. This is accomplished by associating a table with initial (FROM) and final (TO) cell co-ordinates to the ***route***, generating a new attribute for each quality parameter. Figure 2 shows the graphical representation of the ***cell*** theme and associated attributes, in this case just the length; more features will be added later. As a result, the pre-processing phase provides the preliminary data needed to accommodate the results of the model computation. A table of attributes of appropriate dimensions is in fact already available to be later filled with the quality data produced by the river model in the Matlab environment.

Post-processing

After the river quality module has produced the results in the Matlab environment, they have to be transferred back into the client environment controlled by ArcVIEW. This is done by storing the data in a set of temporary ASCII files. Transferring these data to ArcVIEW is accomplished by adding new attributes to the cell theme, one for each component of the water quality model. Figure 3 gives an example of transferring the dissolved BOD (BODd) data generated by the Matlab model unto the complete cell theme back in ArcVIEW.

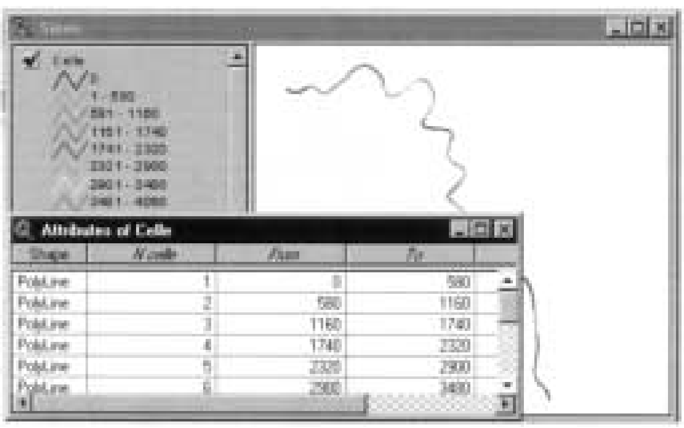

Figure 2 Definition of a cell theme and related attributes

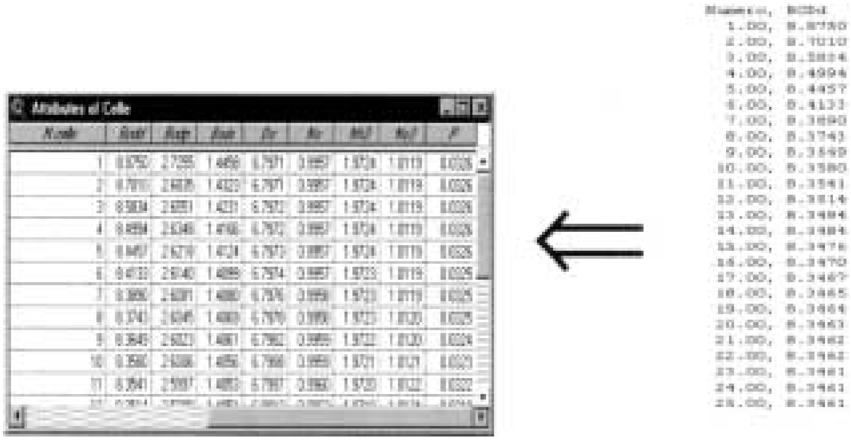

Figure 3 Transforming Matlab model results into new attributes of the cell theme in ArcVIEW

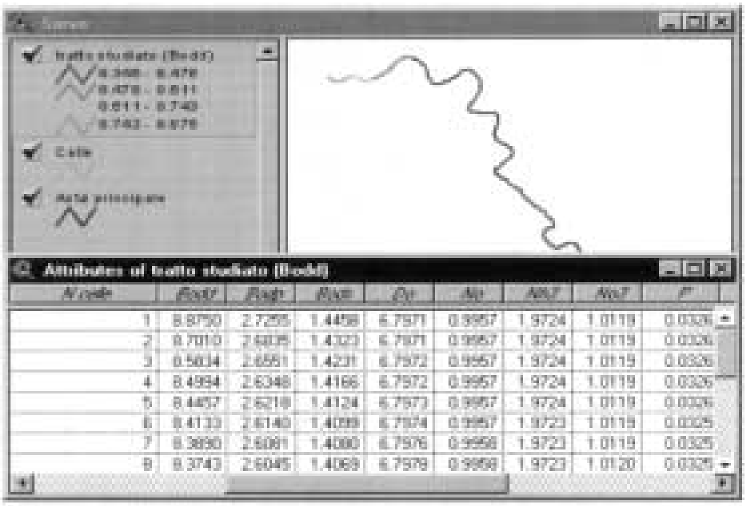

Figure 4 Representation of the attribute BODd in the cell theme with the *equal interval* method

After the data are imported into a theme, their graphical properties should be defined for visual output. In this case a colour classification has been adopted, but other features could be introduced, such as symbols. Since classification can be based on any information associated to them, each quality parameter can be used as a basis for graphical representation. As an example, Figure 4 shows the representation of the attribute “Dissolved BOD” (BODd) along the selected part of the river reach. The classification of this attribute is based on the so-called *equal interval* method, in which the range of values of the attribute is evenly divided into a specified number of equal intervals, to which a range of colours is associated.

User interface

Since the ArcVIEW client is the only the user interface for the whole application, it should provide the means for defining and running the model, in addition to data display. This is done by augmenting the standard ArcVIEW interface with a customised pull-down menu, which in this case has been named Water Quality, as shown in Figure 5. The Start command initialises the DDE communication, Launch water quality model launches the execution of

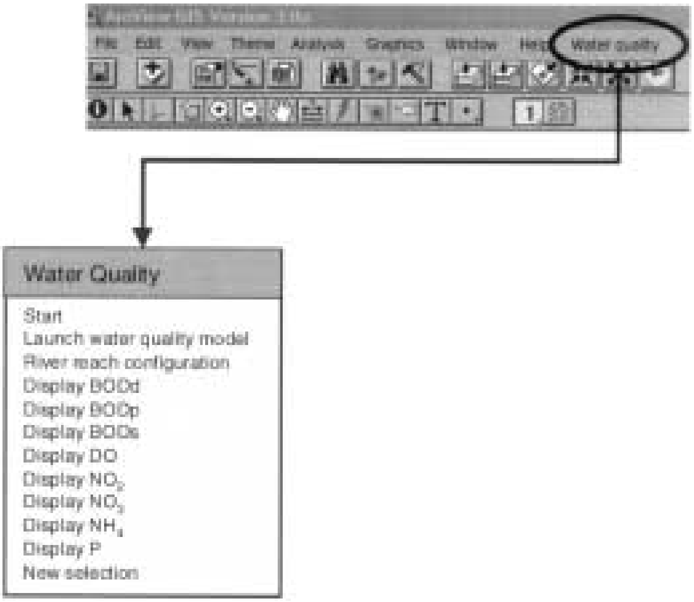

Figure 5 Customised ArcVIEW interface with the additional "Water Quality" pull-down menu

the model simulation in the Matlab environment, whereas River reach configuration is used to define the river characteristics. After all these commands have been executed and the results of the simulation transferred back into ArcVIEW, each quality parameter can be queried through the pull-down menu, activating the corresponding attribute of the cell theme.

River quality model

For this application it was decided that a steady-state model was appropriate, since a continuously changing graphical presentation would appear confusing to the user and constitute a considerable computational burden. The model structure was obtained from the steady-state mono-dimensional diffusion equation in the length x variable, which is related to flow-time τ through the average water velocity u. In Eq. (1) D is the diffusion coefficient, C represents the generic quality parameter concentration and $f(C)$ is the pertinent kinetics.

$$D\frac{\partial^2 C}{\partial x^2} - u\frac{\partial^2 C}{\partial x} - f(c) = 0 \qquad x = u \cdot \tau \tag{1}$$

The basic parameters included in the model are BOD in the three forms (dissolved, particulate, sediment), dissolved oxygen, nitrogen (ammonia, nitrite, nitrate) and phosphorus (total inorganic P). The model kinetics was based on QUAL2E public domain model (Barnes and Barnwell, 1987) and the relevant literature (Zsion *et al.*, 1978; Tchobanoglous and Schroeder, 1985; Jørgensen and Gromieç, 1989; Chapra, 1997).

To adapt the model to the cell partition of the river reach defined in ArcVIEW, Eq. (1) must be integrated along the river reach and the results discretised accordingly. The simulation is performed by a Simulink model, which is controlled by a Matlab script specifying, among other parameters, the initial conditions (C_0, C_0'). It is assumed that the kinetic parameters in the quality model have already been calibrated for the application at hand, or else literature values (e.g. Bowie *et al.*, 1985; Brown and Barnwell, 1987) can be used. Since the initial conditions required to run the quality model are generally unknown, two cases may occur: either only the concentrations at the reach ends C_{up} and C_{down} are

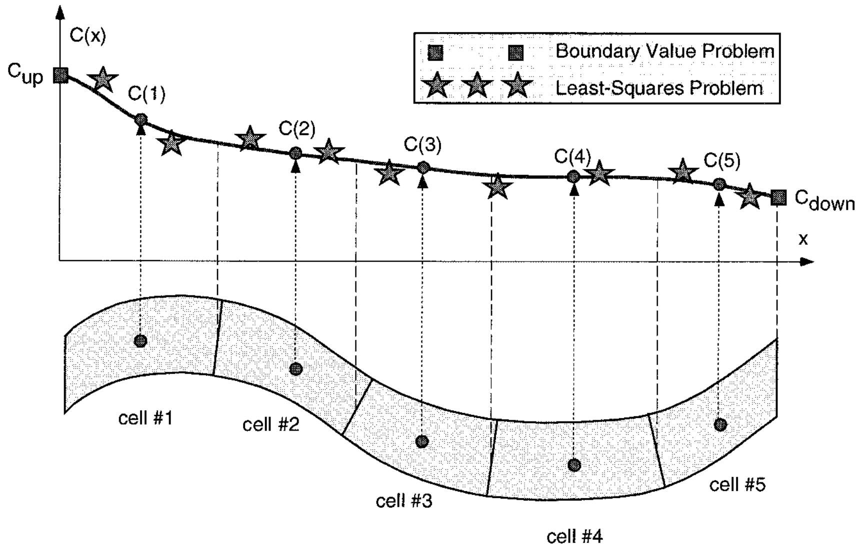

Figure 6 Solving the steady-state quality model, depending of the type of numerical conditions

available, or a set of measurements along the reach is given. In the first case, C_0=C_{up} and a boundary value problem must be solved to determine C_0' as a function C_{down} . In particular, C_0' is determined minimising the difference between the final concentration $C(x=L)$ at the end of the reach and the given value C_{down}. This can be done using a shooting method (Quinney, 1987). In the second case, a least-squares solution is sought, using a numerical search to minimise the error functional of the squared sum of concentration errors as a function of the initial derivative C_0'. A modified simplex search (Marsili-Libelli, 1992) has been used for this application:

$$\begin{cases} \text{Boundary-Value Problem} & C_0' = \arg\min\left(\left|C(x=L) - C_{down}\right|\right) \\ \text{Least-Squares Problem} & C_0' = \arg\min\left(\sum_{i=1}^{N}\left(C_i^m - C_i^{\exp}\right)^2\right) \end{cases} \tag{2}$$

In Eq. (2) N is the number of experimental data and

$$\left\{C_i^m, C_i^{\exp}, i = 1, 2, ..., N\right\}$$

are the sets of model responses and experimental data respectively.

The continuous solution thus obtained is approximated to represent the average concentration in each cell, as shown in Figure 6.

Application to a case study

To demonstrate the procedure, a reach of the Sieve river, near Florence (Italy), 14 km long was considered. In this case a municipal wastewater treatment plant discharges into the upstream end and the downstream quality is measured. A hydrological digital map of the area was already available and a river quality model had already been determined for the reach being considered. Starting from this premises, the pertinent ArcVIEW objects and themes were created, with the result that the water quality simulations produced by the Matlab model could be queried via ArcVIEW. As an example, Figure 7 shows the reach segmentation using different colours to represent the DO concentration along the reach. It can be seen that the colour near the wastewater treatment plant (in the upper left corner) corresponds to relatively lower concentrations, whereas the downstream parts of the reach

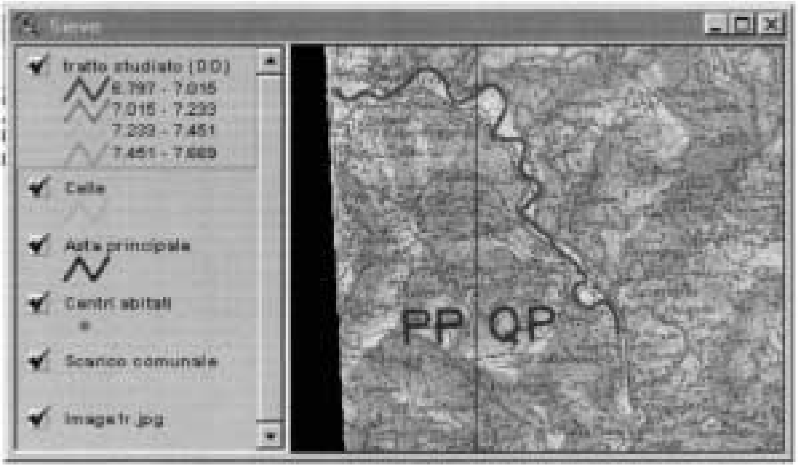

Figure 7 Application of the method to a reach of the Sieve river. The DO concentrations are shown

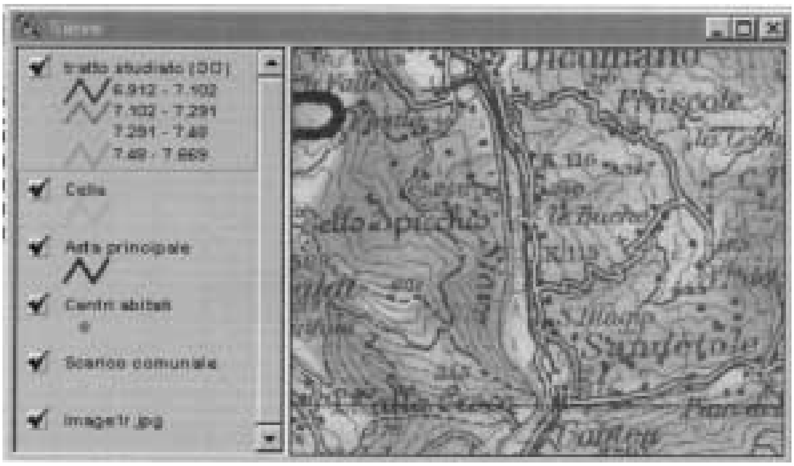

Figure 8 A zoomed-in view of the downstream part of the reach. The colour code for the DO ranges is different from that of Figure 7

exhibit a progressively higher DO concentration, as a result of river self-purification dynamics.

If the map is zoomed-in a finer scale of details is obtained and the colour code is changed to accommodate the range of existing values, as shown in Figure 8.

Conclusion

This paper has proposed a method to interface a GIS with a numerical implementation of a water quality model. The research was stimulated by the fact that normally a river quality modelling problem is initially conceived in the geographical environment and that most simulation programs have a fairly weak user interface or any built-in facility for spatial placement of data. To integrate these two computing environments a client/server architecture was selected, with ArcVIEW acting as a client and Matlab as the server. Special features, termed river cells, had to be created in the ArcVIEW environment to accommodate the quality data produced by the quality model. The data exchange is performed through a very simple Inter Application Communication (IAC) such as Dynamic Data Exchange (DDE) procedure, which is supported by both environments. The client serves also as a user interface, from which the river characteristics can be specified and the results of the simulation queried. The advantage of the solution is that the geographical base can be entered once and for all, whereas the query phase can be modified according to the user's changing needs.

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